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BEAM INSTRUMENTATION FORESEEN FOR LHC

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ABSTRACT

A preliminary estimate of the instrumentation needed for monitoring the LHC itself and the beams in its transfer lines is given. Emphasis is put on the particularities of the LHC project such as the protection of the magnets against quenches provoked by beam losses.

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1. INTRODUCTION

LHC will be a multiparticle collider. It will permit proton-proton, electron-proton, and ion-ion collisions. The project consists primarily of the addition to the existing LEP tunnel of a superconducting magnet system with two beam channels located in a common yoke and cryostat [1].

Eight intersection regions are foreseen; three of them being reserved for physics experiments. The main parameters in p-p mode, which are of interest for the present report, are: (the same symbols will be used later on)

Injection energy (E_i)	0.45 TeV
Maximum energy for $B = 10$ T	7.70 TeV
Luminosity (L)	$1.65 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
Number of bunches	4725
Bunch spacing (X)	4.5 m ($T_0 = 15$ ns)
β values at intersection points β^*	0.5 m
Normalized emittance $\epsilon_n = \sigma^2 \gamma / \beta$	$3.75 \mu\text{m}$
Bunch length (σ_L)	0.075 m
Particles per bunch (N)	10^{11}
Circulating current (I (4.8×10^{14} p))	0.85 A
Revolution frequency (f_r)	11.245 kHz ($T_r = 88.9 \mu\text{s}$)

The definition of emittance, as given in the above table, is that which is generally used for LHC studies, with σ being the rms value of the beam width. We use it here for consistence with other papers on the LHC.

For preliminary tests and at each setting-up, in order to avoid a magnet quench due to accidental losses during the transfer, injection and acceleration of the beam, a pilot beam is foreseen. It will consist of a single bunch of 10^9 p.

For most of the detectors the large ratio between the nominal current "I" and the test beam current will require a wide dynamic range, whereas a high sensitivity is needed for monitoring the pilot (or test) beam. The large energy variation together with the various kinds of particles must also be taken into account.

To reduce the risk of a magnet quench beam-loss detection will play an important role. A special timing system and some specific control requirements will be needed (not described here). A large number of detectors and equipment, also including the transfer lines, are foreseen. Therefore a good choice of the monitors is important from the onset of the project.

2. BEAM POSITION PICKUP

2.1 Beam Properties

As mentioned before, the beam position system must be able to cope with:

- the pilot or test beam consisting of one single bunch of 10^9 p, the intensity of which is $1.8 \mu\text{A}$. Its Fourier spectrum is made of harmonics of the revolution frequency $f_r = 11.245 \text{ kHz}$,
- the nominal beam consisting of 4725 bunches of 10^{11} p each spaced by 15 ns. The Fourier spectrum harmonics are multiples of 66.8 MHz. The total dc current is 0.85 A,
- in the e-p mode: 508 bunches of 3×10^{11} p/bunch spaced by 165 ns. The harmonics are spaced by 6.06 MHz,
- for ion-ion collisions: 800 bunches of 6.2×10^7 ions/bunch, spaced by 105 ns.

2.2 Type of Detector [2]

Matched strip lines are favored, although no use is made of their directionality. The fact that they are matched to 50Ω is beneficial for longitudinal and transverse impedance considerations.

Most of the pickups consist of two strip lines measuring the horizontal or the vertical planes. Less pickup stations measure both planes. The strip lines should be in the shadow of the direct synchrotron radiation. They are fixed together with the quadrupole in the normal superconducting cells. The accuracy with the quadrupole magnetic axis is expected to be better than 0.1 mm. The monitor is kept at 5°K so that the power dissipation at the ends must be small.

The overall coupling impedance with the beam is $Z_l/n = 0.108 \Omega$, $\beta_{av}Z_t = 486 \text{ M}\Omega$.

2.3 Output Signal Voltage for one Strip Line

We consider a beam with a Gaussian longitudinal distribution ($\sigma_L = 0.075 \text{ m}$). Bunches are spaced by X meters such that the Fourier decomposition consists of harmonics of the fundamental frequency $f_0 = 1/T_0 = c/X$. The signal is processed at the extremity of a cable of length " l " which gives an attenuation A . For a centered beam, the amplitude V of the n^{th} harmonic of the output signal is given by:

$$V = 60 \ell n \left(\frac{b}{a} \right) \sin \left(2\pi n \frac{\ell s}{X} \right) \left(\frac{Q_0}{T_0} \right) \exp \left[-2 \left(\frac{\pi n \sigma_L}{X} \right)^2 \right] A \quad [\text{Volt}]$$

$$V = V_i A$$

$a, b, \ell s$ = pickup dimensions (see Fig. 1a)

Q_0 = charge of the bunch; $Q_0 = Nq$

V_i = voltage at the strip-line output at frequency $f = nf_0$

Example: $a = 0.021 \text{ m}$, $b = 0.0306 \text{ m}$, $\ell s = 0.374 \text{ m}$; The cable of length $\ell = 750 \text{ m}$ is an industrial coaxial cable of good quality. One obtains the data given in Table 1.

Table 1

Frequency f (MHz)	N	T_0 $X = cT_0$	V_i (Volt)	V (Volt)
66.8	10^{11}	15 ns	12.7	1.90
66.8	10^9	88.92 μ s	21.4×10^{-6}	3.2×10^{-6}
200.4	10^{11}	15 ns	22.8	0.86
200.4	10^9	88.92 μ s	38.5×10^{-6}	1.46×10^{-6}

In the case where $N = 10^{11}$ p and $T_0 = 15$ ns the power at the output of each strip line is about 25 W whereas at the end of a cable of length $\ell = 300$ m it is 1.5 W (if $\ell = 750$ m, $P = 67$ mW).

If the beam is off-centered, different voltages will be seen by the strip line according to the formula

$$V(\varphi, x, z) = V(\varphi, 0, 0) \frac{1 - (x^2 + z^2)}{1 + (x^2 + z^2) - 2(x \cos \varphi + z \sin \varphi)}$$

In view of the importance of the pickup system, studies are presently under way [3].

2.4 Data Processing

Taking into account the smallest distance between bunches, 66.8 MHz or its multiple, more explicitly 200.4 MHz, will be the working frequency. Presently, the choice is oriented towards a homodyne type electronics.

The position will thus be given by the ratio of the difference to the sum signal (Fig. 1b).

$$x \text{ (or } z) = C \frac{A - B}{A + B} = C \frac{\Delta}{\Sigma}, \quad C = \text{calibration factor (in m)}$$

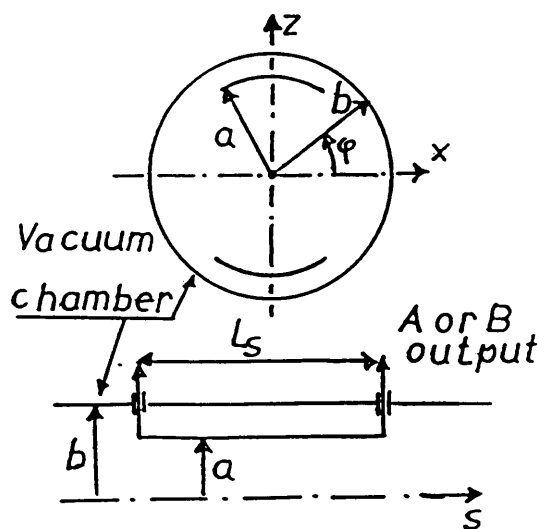


Figure 1a

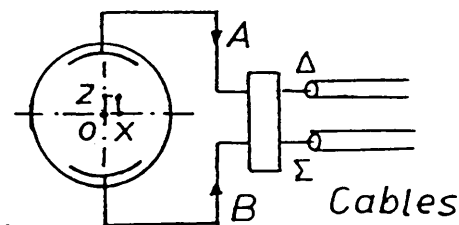


Figure 1b

Fig. 1

With this technique, the accuracy is fundamentally given by the "overall equivalent noise voltage amplitude" (i.e. the noise signal and uncertainties introduced by the electronic system). This will be quite critical in the case of a pilot bunch where Σ is rather small. For closed orbit measurements, however, the signals may be integrated over many turns thus giving a better accuracy. For a pilot bunch, the expected resolutions are 0.3 mm for the closed orbit and 1 mm for the trajectory.

A few selected pickups will be connected to a phase detector to provide a fast detection of the beam excursion and a subsequent alarm. The normalization to intensity will be made with the sum signal. For this application, fast conversion into beam position is more important than high precision.

2.5 Number of Position Pickups

Type	Ring	Transfer lines
Horizontal	400	44
Vertical	400	44
Horizontal + Vertical	286	0

3. SPECIAL PICKUPS

Their number is rather small and they will be used for special purposes described below.

3.1 Longitudinal Wall Current Monitor (Fig. 2)

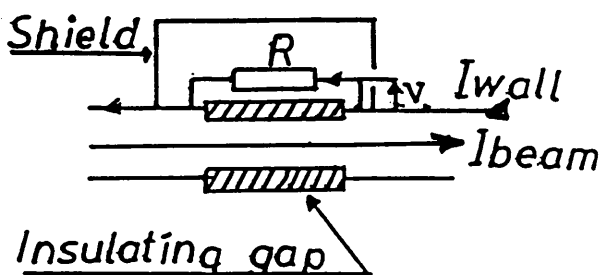


Fig. 2

It can be regarded as an AC current transformer. Its upper frequency limit (3 GHz) will allow the observation of the shape and phase of bunches and their oscillatory behavior.

By loading the volume of the shield with ferrite the frequency range is extended downwards to about 100 kHz.

3.2 Position Sensitive Wall Current Monitor

Based on the same principle as above but using resistances at opposite positions, it will permit the observation of transverse oscillations. Horizontal and vertical signals are obtained from a single monitor within the bandwidth 10 MHz to 1.5 GHz.

3.3 Electrostatic Pickups

They can be used up to 500 MHz. Special very low frequency pickups will descend to a fraction of the revolution frequency, say 2 kHz, so that the lowest mode of coherent transverse instabilities at $(n \pm Q)f_r$ can be observed. They can also be used as resonant pickups.

3.4 Strip-Line Pickups

They are useful for spectral analysis of the beam. By changing the terminations at the feedthroughs they are easily adapted to varying requirements and their frequency response can be tailored by shaping the width of the electrodes.

3.5 Schottky Pickups

They are very wide-band and sensitive pickups for measuring the statistical fluctuations of the beam. Many types can be foreseen like coupler (in series or in parallel), resonant cavities or progressive wave cavities, and they will provide important information on the momentum spread, rms betatron amplitude, synchrotron frequencies, Q-values, etc.

3.6 Many industrial instruments, like fast oscilloscopes, spectrum analyzers, transient recorders, etc. will be used together with these special monitors. The large required bandwidth implies that they should be located near the LHC tunnel.

3.7 Two of each of the above-mentioned detectors are foreseen.

4. INTENSITY MEASUREMENTS

Intensity will be measured with a variety of beam transformers:

- **Fast beam transformers:** their principle of operation is shown in Fig. 3 where the beam acts as the primary circuit which gives a voltage at the output of a secondary circuit. They are used mainly to observe the passage of the beam and the timing of the bunches.

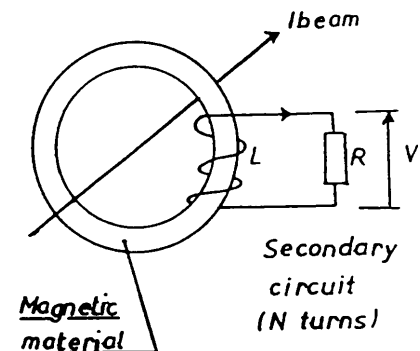


Fig. 3

- **Integrating beam transformers** are based on the same principle as the fast beam transformer but their signals undergo digital data treatment. The precision, typically 1%, is perfectly adequate for monitoring operational performance, but will not permit injection efficiency to be determined with a resolution corresponding to permissible the beam loss (see section 5)
- **dc beam transformers** are based on the principle of magnetic amplifiers and should be able to measure intensities from 0.1 μA to 1 A. In the present state of the art it seems impossible, due to thermal and daily drifts, to cover this range. In consequence, it is expected to use two transformers (one covering the range 0.1 μA to 0.1 A and the other the range 10 μA to 1 A).

4.1 Numbers

Type	Transfer SPS-LHC	Transfer to dumps	Ring	Total
Fast	2	2	2	6
Integrating	4	2	2	8
dc	0	0	4	4
dc, low intensity	0	0	2	2

5. BEAM-LOSS DETECTION

The high rate of collisions between the two proton beams implied by the LHC high luminosity also implies a high rate of small angle scattering resulting in beam halo growth and, consequently, continuous and important losses which may cause a magnet quench.

The expected luminosity at each intersection point is $L = 1.65 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. The total p-p interaction cross section is $\sigma = 100 \text{ mb}$ from which 40 mb concern the elastic cross section. After one inelastic event the particles are lost in the interaction region where they are produced. After one elastic event the particles are emitted within angles comparable to the beam divergence and can create losses all around the machine. The rate for losses will thus be, when LHC operates with three intersection regions:

$$\dot{n} = L \times \sigma \times 3 = 2 \times 10^9 \text{ s}^{-1} \text{ for each beam}$$

Taking into account other effects like beam-beam, intrabeam scattering, magnet non-linearities, power supply ripple, this number has to be raised to 4×10^9 p/s per beam.

It is estimated that, at 7.7 TeV the maximum loss rate at any given point must not be larger than 10^7 p/s to avoid quenching a SC dipole. That shows that beam monitors must be able to measure a loss of 10^6 p/s to reliably detect a potentially dangerous situation.

5.1 Detector

Three possibilities will be considered:

- A ionization chamber filled with air at atmospheric pressure. The chamber used in SPS has 10 cm diameter and is 25 cm long.
- Coaxial cables, a few meters long, are used as ionization chambers. This makes the choice of the detector position less critical.
- A metal tube, 3 to 6 m long, with a thin wire along its center. Filled with argon it works like a proportional chamber with a gain of ~ 1000 . This is the preferred solution and a prototype is under development.

The detectors will be placed around the machine, at locations where the betatron amplitude is maximum. They will be attached to the dipole cryostats. In total, there will be about 1200 of them.

5.2 Electronics

Each ionization chamber (or tube) has its own electronics. The required large dynamic range could be covered with charge-to-frequency converters. Each channel will have a maximum threshold which will be set locally while lower levels can be selected through the control system. When the integrated charge on any of the detector exceeds the threshold, an alarm is given and a trigger can be created to dump the beam. This is an independent circuit, not relying on the control system.

The whole system must be very reliable and one must be able to test it at any time. This can be done by raising the power supply in steps, or applying test currents. Shift registers memories will permit a post-mortem diagnostic.

6. TRANSVERSE PROFILE MONITORS

6.1 Beam Properties

The LHC normalized emittance is $\epsilon_n = 3.75 \mu\text{m}$ such that the emittance $\epsilon = \epsilon_n/\gamma$ is very small.

Some values of $2\sigma = 2\sqrt{\beta_{H,V}\epsilon_n / \gamma}$ are given below.

	0.45 TeV		7.7 TeV	
Arc				
β (m)	29.5	169.5	29.5	168.5
2σ (mm)	0.96	2.3	0.225	0.55
Interaction region				
β (m)	4	521	0.24	5019
2σ (mm)	0.355	4.04	0.021	2.97

Thus, very narrow profiles have to be resolved.

6.2 Transfer Lines and Transfer to Dumps

TV cameras observing the light from scintillator screens will play an important role.

Secondary emission monitors (SEM) used in sets of 3 will give the beam emittance parameter and provide information on the injection matching.

6.3 LHC Ring

Two types of detectors are considered: wire scanners and "synchrotron light monitors"

Wire scanners [4]

A thin carbon wire (diameter $d = 30 \times 10^{-6}$ m) is scanned through the beam either vertically or horizontally. The profile is obtained by the use of scintillators detecting the secondary particles issued from the interaction of the beam with the fibre. One must mainly consider the heating of the wire, resolution and precision and the effects on the proton beam.

- **Heating** - Experiments made at SPS [5] have shown that with a carbon fiber of $d = 30 \mu\text{m}$ traversing a beam of $\sigma = 1 \times 10^{-3}$ m and for $N' = 2 \times 10^{13}$ protons, the non-destructive speed v' must be larger than 0.2 ms^{-1} . If we consider that the temperature increase is proportional to $N/v\sigma$ applied to LHC (for the same σ but $N = 4.8 \times 10^{14}$ p) this implies a speed $v \cong 5 \text{ ms}^{-1}$, which seems feasible. Of course, smaller beams ($\sigma = 0.1$ mm) will require a speed which does not seem technically realizable.
- **Precision, resolution** - If we need to measure at least 20 points over a width of $4\sigma = 4$ mm the sampling time will be $20 \mu\text{s}$ for $v = 20 \text{ ms}^{-1}$. The vibration amplitude of the wire must be kept smaller than the fiber diameter.
- **Effect on the beam** - The emittance growth per scan $d\epsilon/dn$ due to Coulomb scattering is approximately given by:

$$\frac{1}{\pi} \frac{d\varepsilon_{H,v}}{dn} = \frac{2.53 \times 10^{-4} \beta_{H,v} d^2 f_r}{P^2 v L_{rad}}$$

where P (GeV/c) = momentum, $\beta_{h,v}$ = beta values, v = speed, L_{rad} = radiation length ($L_{rad} = 0.188$ m for carbon). It is negligible.

The particle loss per traversal is given by

$$\frac{1}{N} \frac{dN}{dn} = \left(\frac{\pi d}{4} \right)^2 \frac{f_r}{v L_n}$$

where L_n = nuclear scattering length ($L_n = 0.66$ m for carbon). For $d = 30$ μ m, $v = 10$ m/s, we obtain $dN/dn = N \times 2.35 \times 10^{-6} = 1.13 \times 10^9$ p, which is not negligible when considering the influence on the physics experiments and the risks of quenching a magnet as it is a localized loss.

We can conclude that the wire scanner must be used with care. It should concern mainly low-density beams and, of course, will be used at low energies (0.45 TeV). Up to 8 wire scanners are foreseen, 4 of them will have speeds of up to 2 m/s and 4 a fixed high speed of the order of 20 m/s.

Synchrotron light monitors

This device is of course non-destructive. A useful parameter is the critical wavelength defined by $\lambda_c = (2\pi/3)(\rho/\gamma^3)$, i.e for $E = 7.7$ TeV: $\lambda_c = 10$ nm, and for $E = 0.45$ TeV: $\lambda_c = 50$ μ m. Optical image detectors operating in the UV and/or visible range (200 to 800 nm) give valuable results for a power density ≥ 1 nW/cm².

- Normal bending magnets - According to λ_c one can foresee that it would be difficult to observe any profile for low energies. In fact, computations show that for $N = 10^{14}$ p an observation can be made for $E > 1.2$ TeV, and for $N = 10^9$ p for $E > 2$ TeV.
- Edge effect - Experiments made at SPS [6] show that good results are obtained for $N > 10^{13}$ p and $E > 0.45$ TeV. However, this assumes a sharp discontinuity (10 to 90% within about 15 cm) of the magnetic field at the edge of the dipole. This could not be the case for LHC penalizing, a priori, the only method using synchrotron light which would allow us to measure profiles at 0.45 TeV.
- Short magnet [7] - A short dedicated magnet with a magnetic field $B(s) = B_0/(1+s^2/lm^2)$, $B_0 = 1$ T, $lm = 0.3$ m, will give sufficient power in the UV range ($\lambda = 150$ to 350 nm) above 0.65 TeV. At this energy, when filtering out the horizontal polarization, the diffraction width is about 60 μ m when $\lambda = 200$ nm. Of course, the diffraction pattern increases with energy. Studies oriented towards some adequate magnet field "shaping" are to be pursued.

As a conclusion there will be some challenge to observe profiles, at low energies, when using synchrotron radiation. The use of x rays and of the beam-beam synchrotron radiation can be envisaged at top energy.

For each beam one horizontal and one vertical profile monitor is foreseen (total = 4).

7. TUNE MEASUREMENT

Betatron tune and chromaticity must be measured throughout the cycle with high precision. The transverse feedback system, although not a part of instrumentation, can be used for this. For a tune measurement its damping is interrupted for a brief interval, typically 10 to 100 ms, during which it is used to excite coherent transverse oscillations observed with position pickups. After that, the damping action is re-established. In this way a series of measurements can be performed over the cycle.

The signals from the pickups will lie in a frequency range 2 kHz-34 MHz. Since the chromaticity causes a tune spread, measuring the time taken for the oscillations to lose their coherence, seen as a decrease of the pickup signal amplitude, allows the determination of the chromaticity. At the small amplitudes at which the measurement is performed, the contribution to the incoherence of the oscillations from other non-linear effects, e.g. octupole fields, will be negligible. The same type of electronics foreseen for the tune measurement can also permit the study of coupling and the measurement of betatron phase advance.

The exploration of tune and aperture at large oscillation amplitudes requires powerful kickers (in the horizontal plane the injection kickers may be used). These are not considered as belonging to instrumentation.

8. INSTRUMENTATION FOR TRANSFER LINES

Under this heading are grouped the instruments for monitoring ejection from the SPS, transfer and injection into the LHC, ejection from the LHC and transfer to the two beam dumps.

The lines will be equipped with the same type of monitors mentioned before.

Transfer line	Pickups		SEM-grids H + V	Screen and TV	Beam transformer	Loss monitors	Screens 40 cm
	H	V					
TI48	24	24	6	10	2	40	0
TI51	24	24	3	10	2	20	0
Dumps	6	6	0	6	2	0	2

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